

A Comprehensive Model for Performance Prediction of Electro-Optical Systems

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LONG-TERM GOALS

The long-term goals of this effort are to provide reliable performance prediction and accurate system simulation capabilities for underwater electro-optical identification (EOID) systems. The Electro-Optical Detection Simulator (EODES) suite of numerical models developed under this program will predict the impact of environmental conditions, system parameters (e.g., apertures and PMT gains), and operational settings (e.g., platform speed and altitude) on system performance. The models are designed to support mine countermeasures (MCM) mission planning, system design analysis, and operator training. It is anticipated that the performance prediction models will also be integrated into Tactical Decision Aids (TDAs), specifically the Mine Warfare Environmental Decision Aid Library (MEDAL) and/or the Environmental Post Mission Analysis (EPMA) station.

The two most prominent sensor technologies in this area are Laser Line Scan (LLS) and Streak Tube Imaging Lidar (STIL). Examples of systems using these technologies are the AN/AQS-24 (using LLS) and a variant of the AN/AQS-20 (using STIL) mine-hunting systems. High-fidelity models for these systems have already been incorporated into the EODES software. The EODES LLS model is currently undergoing quality assurance verification preliminary to its inclusion as a Navy Standard model in the Oceanographic and Atmospheric Master Library (OAML). The STIL model will be submitted to OAML upon further validation. The Airborne Laser Mine Detection System (ALMDS) also uses a STIL sensor to image underwater objects from an airborne platform. An ALMDS model will also be fully integrated into EODES after further development and validation.

OBJECTIVES

Our objectives are to develop and validate EOID models to compute reliable metrics for the prediction of system/operator performance, and for generating synthetic images of bottom scenes under given environmental conditions and operational settings. These objectives necessitated the development of high-fidelity physical and numerical models to solve the radiative transfer equation and to accurately calculate the time-dependent laser backscatter return. The simulation and performance prediction models for underwater EOID systems are complete and are now being certified for ultimate incorporation into the Navy Standard Oceanographic and Atmospheric Master Library (OAML). All EODES code is written in ANSI C/C++ (and made ISO compliant) to ensure portability across

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computer platforms and to facilitate incorporation within fleet TDAs. Development of new sensor/system models is expedited through code reuse and sharing of common interfaces, making it possible to leverage off previously implemented and validated models.

APPROACH

Performance predictions for underwater EOIDS systems rely on high-fidelity, physics-based simulation models. These models account for the specific design of the system, and include detailed sub-models for the laser source, the receiver, and their geometric configuration. Models for the environmental conditions, such as ambient light, and a complete characterization of the optical medium are incorporated into the EODES code base. The light distribution in the water column from all light sources (laser and ambient) and the collection of backscattered and reflected light are accurately modeled. This requires solutions to the radiative transfer equation in a turbid medium, which we assume to be plane-stratified. We make the assumption of small-angle scattering and use well-known Fourier optics techniques to solve for the light distribution and, then, to derive the received return.

For both the LLS and STIL sensors, along-track scanning is achieved by the forward motion of the sensor platform. For the LLS system the laser source is mechanically scanned in the cross-track direction. For the STIL system the light is emitted in a fan beam, and the received light is processed and converted to a row of grayscale pixel values. A grayscale raster image of the bottom scene is built up as the sensor moves forward in the along-track direction. We have developed accurate simulations of these processes for the LLS and STIL systems in order to generate realistic synthetic images. These simulations require accurate low-level physical models that form a common code base for all system simulation models, and which also form the basis for the performance prediction models.

Performance predictions can be based directly on simulated imagery or on a parametric equation that reflects the image formation process. Simulated images provide a qualitative and subjective means of evaluating performance under prescribed conditions. Parametric models provide objective, quantitative outputs that can be a measure of relative performance, a task satisfaction confidence level, or a task-specific probability of performance measure. EODES uses a parametric performance model that first estimates the image quality under specified environmental conditions, and then relates the image quality estimate to operator performance through semi-empirical models based on actual system imagery and operator performance.

The EODES image quality metric predicts the expected performance of an EOIDS system operating under given environmental conditions and with specified operational settings. The metric does not require the generation of simulated images. We scale the metric to range between 0 and 10, where 0 indicates a complete inability to identify objects within the imagery obtained by the system, and 10 indicates an excellent ability to identify objects. The EODES metric accounts for image degradation due to limited resolution, blurring, contrast loss, and shot noise. It is patterned after the General Image Quality Equation (GIQE) [1,2] and takes the form

$$IQ = \min(10, A \log_{10}(SNR + B)) - C \max(0, GSD - D) - E \sqrt{1 - RER},$$

where A , B , X , Δ , and E are system-dependent coefficients that are derived based on an analysis of actual system data. The EODES image quality equation adapts the GIQE to account for the fact that underwater images are obtained from relatively short standoff distances.

As with the standard GIQE, the above image quality metric involves three measures of image fidelity. The ground sampled distance (GSD) is a measure of the resolution of the system in meters at the depth of the scene (ocean bottom). The relative edge response (RER) is a measure of blurring due to the system optics, geometric spreading of the narrow, collimated laser beam and the collector field-of-view, and volume scattering in the water column. The signal-to-noise ratio (SNR) relates the fraction of light that has reflected from a resolution cell on the ocean bottom (i.e., the scene) to the total amount of light reaching the collector, which includes volume backscatter of both ambient and laser light.

WORK COMPLETED

An EOID performance prediction model was developed based on the GIQE formulation. While the new EODES model depends on the same mid-level variables (the GSD, RER, and SNR), the EODES model provides a new definition for the SNR and involves a very different functional form. This model was validated against LLS data collected during an ONR sponsored field test conducted in August 2001 near Panama City Beach, Florida [4].

A stand-alone version of the LLS performance prediction model (called EODES_LLS) was developed for submission to OAML, and was demonstrated at the RIMPAC-08 exercise conducted in Hawaii in July 2008. This model incorporates the metric described above and can operate in one of two modes: it can predict image quality given the system's operational settings and a characterization of the optical environment; or it can determine the maximum altitude at which the system is expected to produce imagery suitable for the purpose of target identification.

The EODES_LLS code was submitted in August 2008 to OAML along with complete software and technical documentation and a comprehensive test suite. The documentation includes a detailed application programming interface (API) description, a software requirements description, and a software test description. The EODES_LLS code is written in ANSI C/C++ and is portable across computer platforms (it was made ISO compliant for compilation on Windows platforms).

Extensive validation of several EODES components was performed in collaboration with Dr. Fraser Dalgleish at Harbor Branch Oceanographic Institution /Florida Atlantic University (HBOI/FAU). Experimental data acquired under carefully designed and controlled experiments validated the EODES radiative transfer model and the EODES laser backscatter model for several sensor configurations and across a wide range of turbidity levels.

RESULTS

The EODES radiative transfer solver computes the beam spread function (BSF) under the small-angle scattering assumption [3]. The BSF is a fundamental quantity underlying the simulation and performance prediction models. Accurate calculation of the BSF is, therefore, critical to the reliability of all the EOID system models. Extensive laboratory measurements of the BSF were taken at the Harbor Branch Oceanographic Institution (HBOI) campus of Florida Atlantic University (FAU) for several water turbidities and at several different ranges. An example of the validation results is given in Figure 1. It demonstrates very good agreement between the measured and computed BSF as a function of distance from the beam axis, where the beam attenuation coefficient $c = 0.4 \text{ m}^{-1}$ and the radiometer was placed at a range of 7 meters from the laser source.

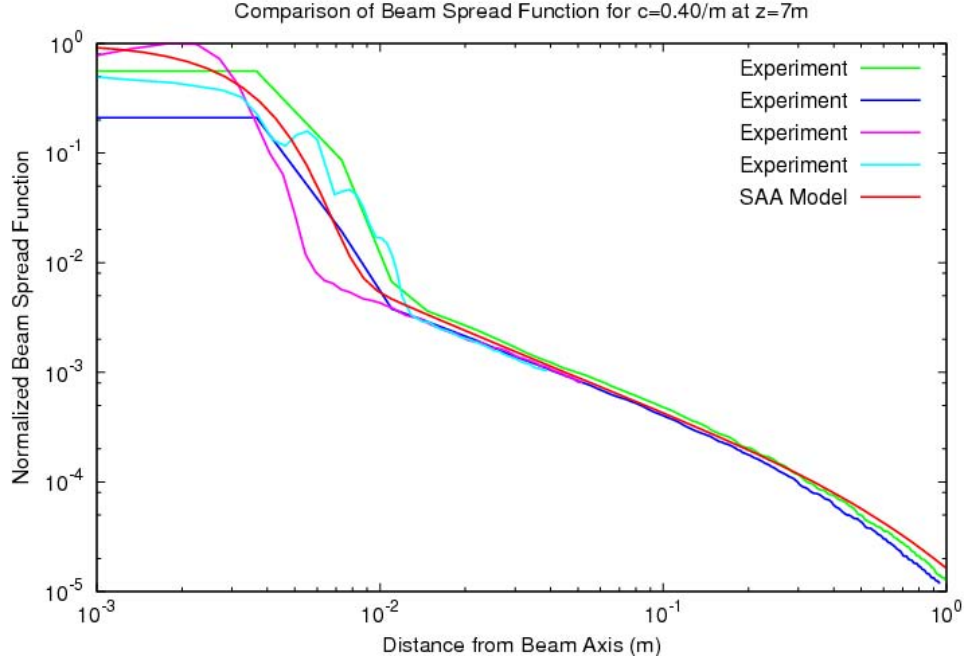


Figure 1: Comparison of four experimental measurements of the BSF with an analytical model based on small-angle scattering. The BSF is plotted on a log-log scale as a function of radial distance from the beam axis.

For underwater EOID imaging systems, a major contributor to the noise level is the volume backscatter from the laser beam as it propagates through the water column. Backscattered light does not interact with the bottom scene and hence carries no useful information. An accurate estimate of the laser backscatter is required to compute the signal-to-noise ratio (SNR), which is a key term in the image quality equation above. Therefore, the overall reliability of the simulation and performance prediction models depends on an accurate estimate of the laser volume backscatter. This computation has been validated against experiments conducted at HBOI/FAU. The experiments involved sending short laser pulses into turbid water and measuring the intensity of the backscattered light as a function of time. Figure 2 is an example of the results obtained when comparing the model calculations to the measured data. In this case the beam attenuation coefficient $c = 0.25 \text{ m}^{-1}$ and the source and receiver separation was set at 376 mm. The second peak in the figure is due to the reflection from a panel placed at 10 meters from the source. The agreement between the backscatter model and the data is excellent.

In most MCM situations the EOID system is power limited, so an accurate estimate of the SNR term in the image quality equation is critical to reliable performance prediction. Figure 3 shows the predicted SNR for data collected at an ONR-sponsored field exercise conducted by NSWC in Panama City Beach (PCB), Florida, in August 2001 [4]. The SNR is plotted against a measure of towbody altitude, which is given in attenuation lengths plus the natural log of the altitude in meters. This dimensionless distance metric is roughly proportional to the power received as a function of distance. During the exercise, the platform was towed at several different altitudes in water of varying turbidity. Each of the LLS runs during the weeklong exercise was color-coded according to whether: all the targets in the imagery could be confidently identified (green); many targets could be identified (light blue); roughly half the targets could be at least tentatively identified (blue); only a small fraction of targets could be

identified (pink); or no targets were identifiable (red) by a human operator. The plot shows that the estimated SNR is itself a reasonably good discriminator of performance, where we observe that the higher the SNR the greater the proportion of identifiable targets.

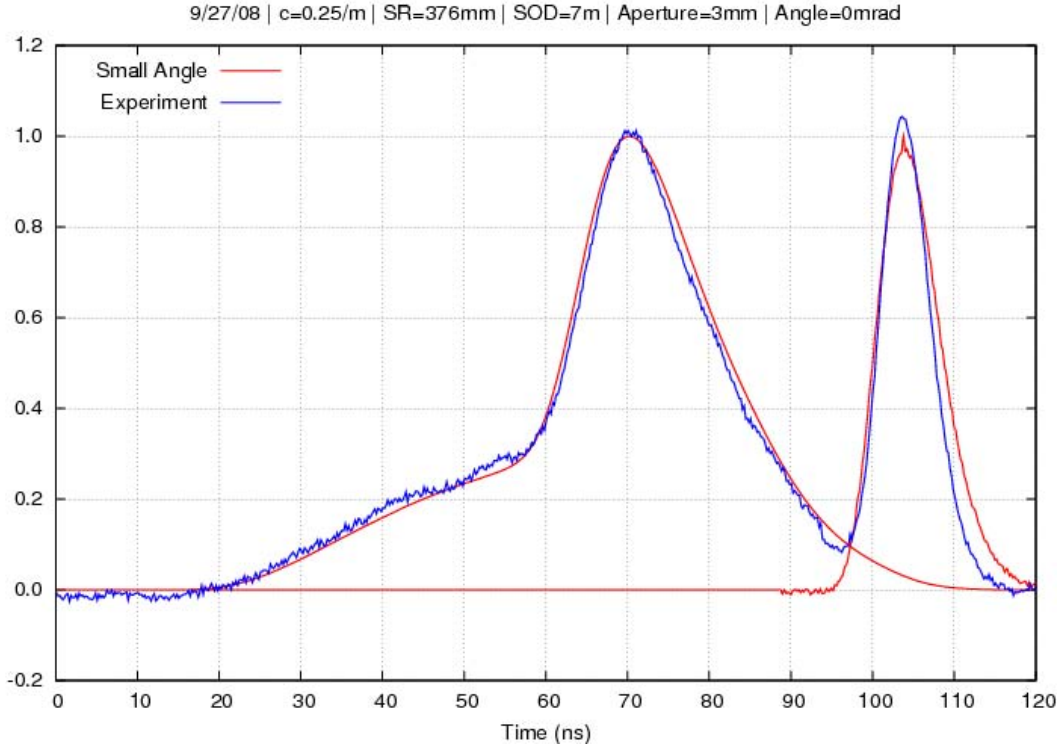


Figure 2: Comparison of experimental data to the EODES semi-analytical model for laser light backscattered as a function of time. A pulse is emitted at time $t=0$, produces backscatter as it propagates through turbid water, and reflects from a target at 10 meters.

Finally, we examine the predictions for image quality as estimated by the above model equation. In Figure 4, estimated image quality is plotted against the same metric described above. We see that the image quality metric is clearly an effective discriminator of performance. We observe that horizontal lines at $IQ=7$ and $IQ=4$ provide very good separation of the data into cases where all targets are readily identifiable (green), where identification of some but not all of the targets is possible (light blue, blue, and pink), and where no targets are identifiable (red). The predictions were made for two different LLS systems under a variety of environmental conditions, so that the approach is applicable across various LLS configurations and specifications. The color-coded data demonstrate a clear and strong correlation between the predicted image quality and the ability of the operator to identify targets from within the imagery. It is envisioned that such predictions of EOID performance over the entire battlespace will aid commanders and mission planners in effectively choosing the operational areas, systems, and tactics.

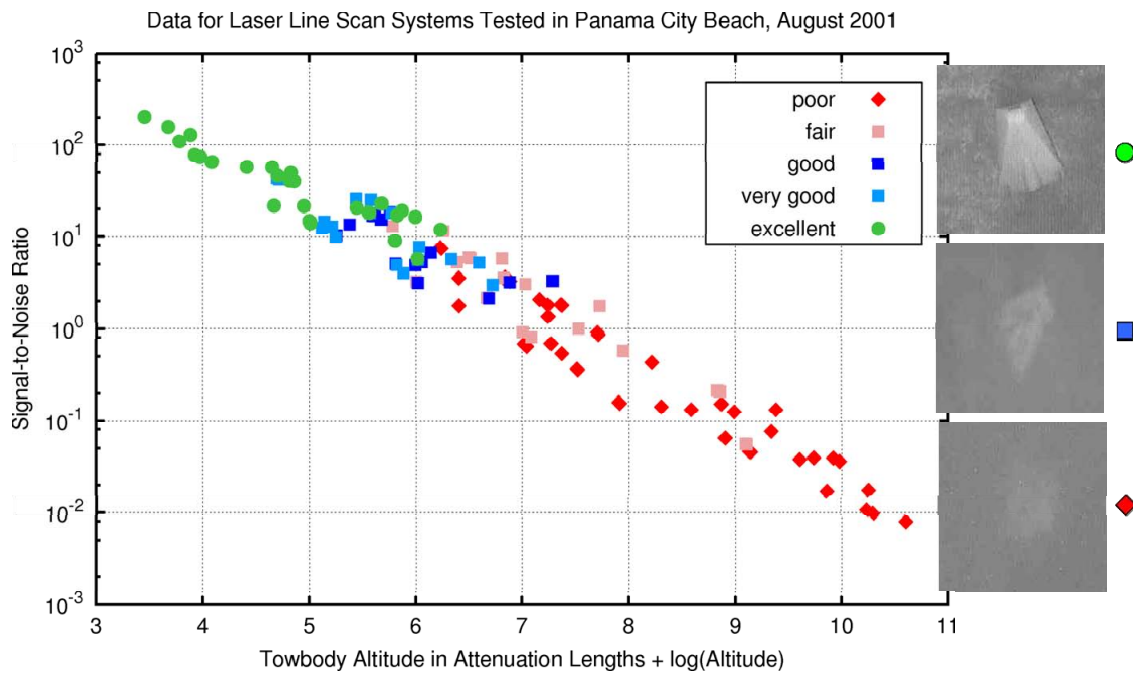


Figure 3: Predicted SNR for the LLS data recorded in Panama City Beach, Florida, in August 2001. Green dots (●) indicate that all targets were readily identifiable in the imagery, blue squares (■) indicate that roughly half the targets were identifiable, and red diamonds (◆) indicate no identifiable targets. The pink (◻) and light blue (◻) squares indicate runs where most of the targets were identifiable or unidentifiable, respectively.

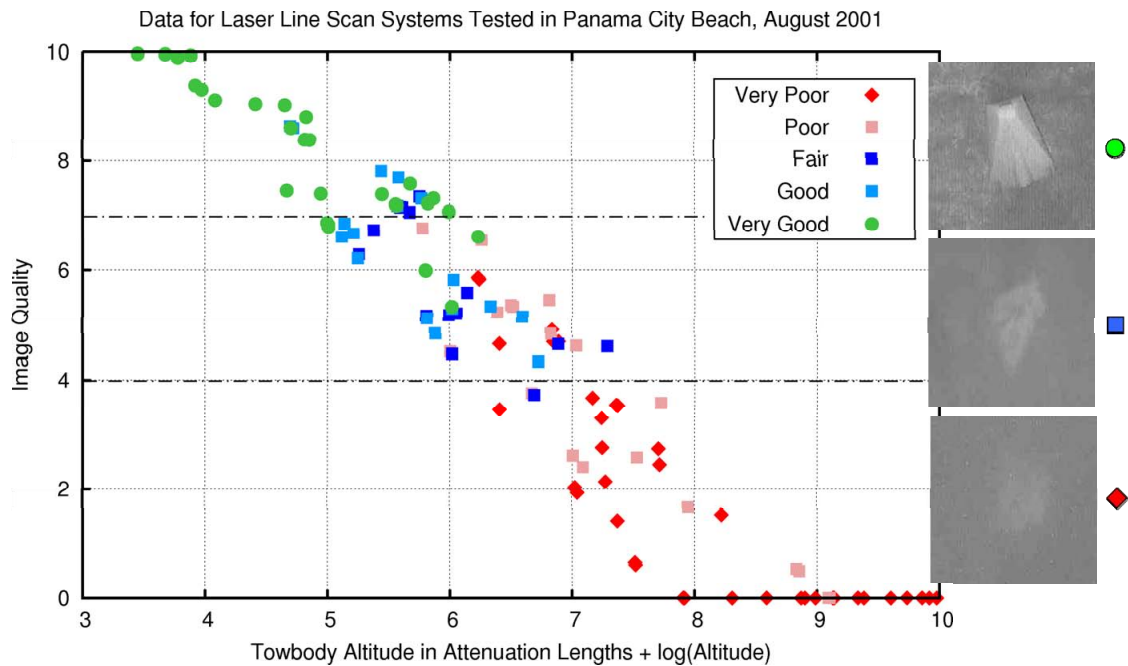


Figure 4: Predicted image quality for the LLS data recorded in Panama City Beach, Florida, in August 2001. Refer to the caption of Figure 3 for a description of the color-coded markers.

IMPACT/APPLICATIONS

When completed and validated, the performance prediction models for LLS, STIL and ALMD systems will be available for distribution and incorporation into Fleet Tactical Decision Aids. These models will facilitate effective MCM mission planning, tactical decision making, and asset allocation. Moreover, the models can be used to maximize system performance by estimating optimal system settings for a given environment. The EODES model suite can also generate synthetic images which are valuable for training human operators, and can also be useful in the development and validation of automatic target recognition algorithms. The system models and radiative transfer solvers within EODES will also become useful design and analysis tools for prospective electro-optical systems.

TRANSITIONS

The models and metrics developed and validated by this work have been used to support MIREM exercises in 2003 and 2005 and the RIMPAC exercises in 2006 and 2008, all of which involved the AQS-24 system. Specifically, for the RIMPAC-08 exercise, the EODES performance prediction model was a key part of the Naval Oceanographic Office (NAVOCEANO) ocean optics and mine warfare demonstration. The EODES models are currently in the process of obtaining OAML certification in preparation for transition to the Naval Oceanographic Office and integration into the MEDAL/EPMA tactical decision aids.

RELATED PROJECTS

This project is closely related to award number N00014-08-M-0007, which provided support for RIMPAC-08, a Naval exercise conducted in June 2008 in Hawaii where we demonstrated how systems for battlespace awareness can work in conjunction with EOID performance prediction models to provide value to MCM mission planners. The same award number also provided support for readying EODES_LLS for submission to the OAML certification process.

Award N00014-04-C-0240 provided support for experimental validation work at FAU/HBOI. Measurements taken there of the beam spread function and laser volume backscatter were essential to demonstrating the reliability of several components of EODES and to preparing the LLS model for OAML accreditation as a Navy Standard.

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